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APPLICATION OF BULK COAL SELF-HEATING TESTS TO LONGWALL OPERATIONS

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ABSTRACT: A new laboratory has been established in the Division of Mining and Minerals Process Engineering, which has refurbished and recommissioned a 2-metre self-heating column built at The University of Queensland (UQ). This equipment overcomes the limitations associated with previous large-scale testing. Repeatable test results are achievable within days instead of months and are far more advanced than any previous work at this scale. The column is ideal for simulating goaf behaviour and for teaching the fundamentals of heating development, including gas detection and analysis. Seventeen test runs have now been completed since the initial recommissioning test in late 2001, with a 100% success rate. Results to date clearly show that moisture transfer is the key factor in coal self-heating development. There is a critical moisture content below which coal oxidation and resultant self-heating is inevitable. This has significant implications for detecting and reducing the risk of a heating in longwall operations. Dried coal as a result of gas drainage will be more susceptible to self-heating as it is predisposed to both heat of wetting from moisture adsorption and accelerated coal oxidation due to ease of access of air to oxidation sites. The off-gas signature associated with the self-heating process appears to be quite complex.

INTRODUCTION

When coal is exposed to air an exothermic reaction takes place (Baum, 1981), which given the right conditions leads to a rise in temperature of the entire coal mass. Whether or not self-heating will occur is governed by the competing mechanisms of heat release from the oxidation reaction and heat losses by convection, conduction and radiation to the surroundings. If heat losses are minimal the coal will be under adiabatic conditions, which promotes self-heating.

One of the most significant hazards faced by longwall operations is coal self-heating leading to spontaneous combustion, which often results in millions of dollars in lost revenue and at frequent intervals has resulted in loss of life. A better understanding of the self-heating process and more definitive ways of assessing the risk of an incident will help improve the management of coal mining, resulting in the prevention of future major disasters.

Preliminary results from new studies of bulk coal self-heating using a 2-metre adiabatic column provide a much clearer picture of the importance of moisture transfer in the self-heating process and the off-gas signature associated with a heating.

BULK SELF-HEATING TESTS

Bulk sample self-heating tests of coal have been applied to a limited extent using medium-scale (40-1000 kilogram) test equipment. Stott (1980) reported the use of a 5m long, 0.6m diameter vertical container in the US. This experiment ran for five months and the coal temperature only rose to 45°C due to insufficient insulation of the outside of the column by normal means. It was recommended that a similar smaller apparatus be constructed with approximate dimensions of 2m long and 0.5m diameter. Chen (1991) followed these recommendations under the supervision of Stott, and built a so-called "Full-Scale Experiments Apparatus", which was 2m long and 0.3m in diameter. The equipment was used to study New Zealand coals ranging in rank from lignite to high volatile bituminous (Stott and Chen, 1992). However, a limitation of these tests was that they did not go beyond 120°C, and thus did not show the full extent of thermal runaway that occurs leading to self-ignition.

Li and Skinner (1986) used a 244cm long cylinder with a 61cm diameter, which featured a conical bottom. Their study showed the development of a hotspot in two tests performed on Black Thunder (Wyoming low sulphur, subbituminous) coal of 10% moisture and no hotspot development with 30% moisture. Monazam, Shadle and Shasmi (1998) were able to model these results using finite difference methods.

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Akgun and Arisoy (1994) also performed investigations using a column. The column was 3m long with a diameter of 0.3m. The features of this column included one spiral heater wound around the aluminium plate of the column's inner wall. The column was mounted at an angle of 25° from the horizontal - because airflow in stockpiles is neither vertical nor horizontal (Akgun and Arisoy, 1994). However airflows in a stockpile were not approximated by the 200 litres/hour airflow at 75°C temperature, which was used. These airflows were used 'in order to reduce the experimental time' (Akgun and Arisoy, 1994). Such airflow can never be referred back to the circumstances under which stockpiles are subjected in real conditions. Also, the use of one heater cannot provide adiabatic conditions along the length of the column.

Arief (1997) developed a column self-heating test apparatus at The University of Queensland (UQ) measuring 2m long and 0.2m in diameter (Figure 1), which was a modified version of the column used by Chen (1991). As suggested by Chen (1991), and from a practical viewpoint, the diameter of the column was reduced so that the amount of sample needed to undertake the experiments was relatively small and the column could be loaded and unloaded relatively easily. The column was used with as-received coal samples that would incorporate a range of particle sizes and moisture states, closely resembling natural conditions. The results of this preliminary use of a medium-scale apparatus to test Australian coals remain unpublished other than a brief conference proceeding paper (Arief and Gillies, 1995). A limited number of tests were performed on coals from two mines near Ispwich up to temperatures of 120°C, and hence the equipment has not been fully utilised for spontaneous combustion research.

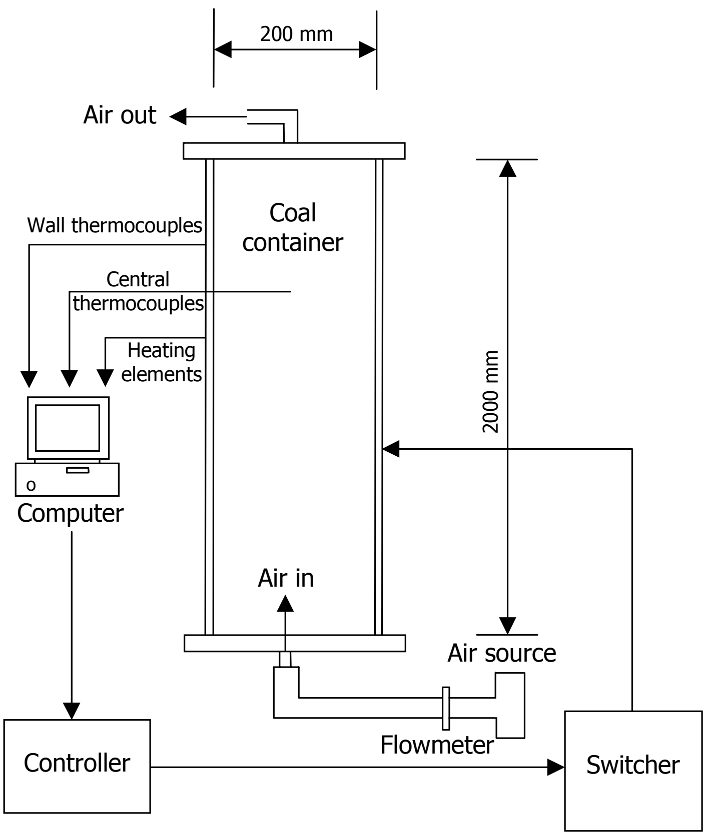

FIG. 1 - Schematic of UQ 2-metre column self-heating apparatus (modified from Arief, 1997)

Large-scale (16 tonne) self-heating tests have been successfully applied at the Queensland Safety in Mines Testing and Research Station (SIMTARS), with the limitation that it can take 6-12 months to generate one result (Cliff et al., 1998). The time taken for these tests is dependent on the physical parameters used in the test (e.g. coal size, moisture content etc.) and the rank of coal, which affects the reactivity. Smith, Miron and Lazzara (1991) performed large-scale spontaneous combustion studies using a 13 short ton chamber, with high-volatile C bituminous coals. One of these coals reached thermal runaway near the centre of the coalbed after 23 days from an initial starting temperature of 30 °C.

In late 2001, the 2-metre column used by Arief (1997) was refurbished and recommissioned at UQ (Beamish *et al.*, 2002). Since then, 17 test runs have been completed with a 100% success rate. From these tests it is clear that the column has a number of significant advantages. These are:

- The test is performed on as-received bulk coal (60 litres or 40-60kg of coal depending on packing density used) up to a maximum temperature of 250°C. This maximum temperature has been progressively established to maintain strict safety standards during testing. To achieve these temperatures, it was found necessary to remove the carpet inner originally used by Arief (1997). The supposed purpose of the carpet inner was to act as a baffler on the sides of the column to prevent air channelling. However, tests on coal before and after the carpet was removed showed no signs of significant changes to the self-heating development in the column.
- Tests results are available in days, with a full history of the self-heating development of the coal. The longest test run to date has taken 28 days to complete, with the majority of tests taking less than 14 days.
- Moisture effects are clearly visible.
- "True" off-gas is liberated and monitored from the self-heating process of the coal, including any moisture driven and gaseous feedback reactions leading to "fire-stink".
- Hotspot development and propagation can be quantified.
- Direct impacts of changes in airflow rate, particle size, air temperature and starting coal temperature can be assessed.
- Effects of the presence of pyrite and seamgas can be assessed.
- Simple coal quality relationships can be determined for any mine. These can also be related back to small-scale adiabatic R_{70} testing.
- Mine strategies to control self-heating can be assessed, including:
  - ventilation changes
  - inertisation
  - inhibition

COLUMN TEST PROCEDURE

Beamish *et al.* (2002) provide a full description of the 2-metre column. A high-volatile bituminous coal sample was supplied from the mining face of a Bowen Basin mine. A size distribution was measured for the as-received sample prior to loading into the column, with a top size of 75mm being applied. The column has a load capacity of approximately 60 litres and for ease of loading 3 x 20 litre plastic sample buckets were used. The column was sealed at the bottom and coal loaded in through the top. As the coal level reached each thermocouple it was pushed into the centre of the coal. Once the column was full, the lid was fitted and sealed and the outlet hoses connected to a water trap, which was in turn connected to the outside atmosphere. At this stage the column was completely sealed with the outlet hose being blocked off and the outside wall heaters of the column were used to stabilise the coal temperature to 40°C in this particular test. Other starting temperatures can be used if the minesite wishes. This process usually happens overnight and the next morning the outlet was reconnected to the outside atmosphere and the air was turned on with a flow of 0.5 litres/minute. Exhaust gas emissions were monitored periodically with a Minigas, which measures oxygen, carbon monoxide, methane and hydrogen sulphide. Gasbag samples were also taken for GC analysis of other gases such as hydrogen, ethane and ethylene.

MOISTURE TRANSFER DURING SELF-HEATING

The temperature history of the coal self-heating is shown in Figures 2 and 3. Stages of heating development have been superimposed on the graphs. The corresponding temperature profile in the column is shown in Figure 4.

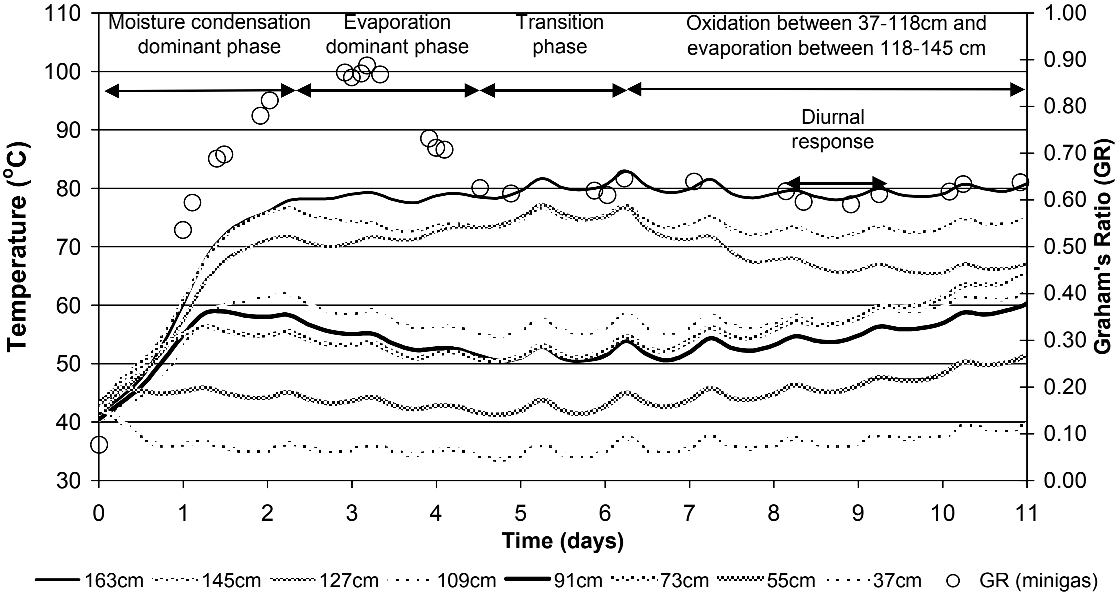

FIG. 2 - Temperature history of a high-volatile bituminous coal self-heating (day 0-11)

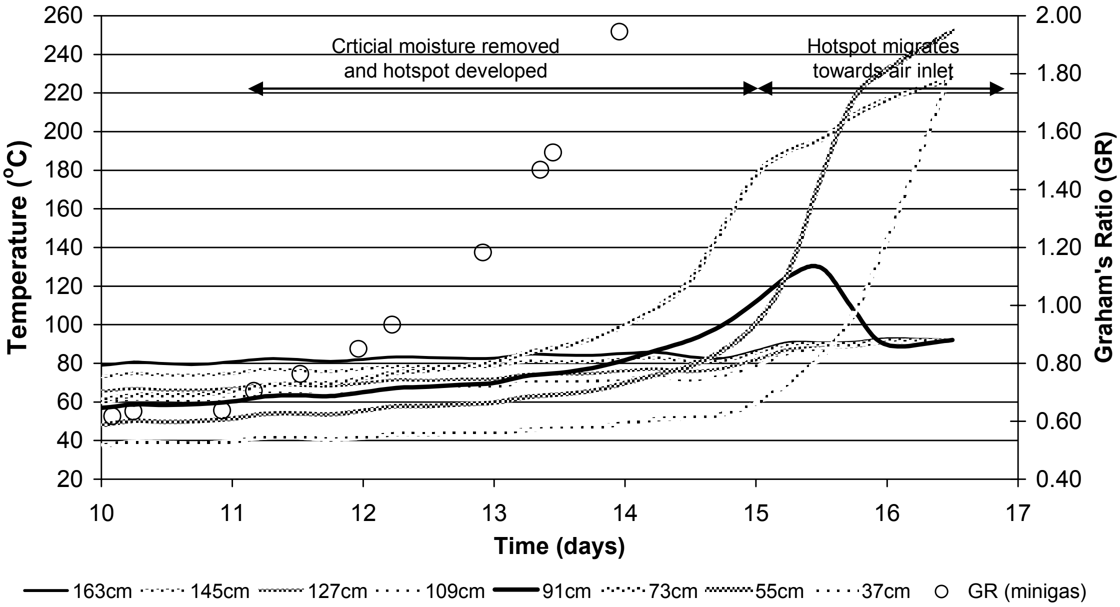

FIG. 3- Temperature history of a high-volatile bituminous coal self-heating (day 10-16.5)

In the initial heating stage, the airstream transfers moisture from the lower part of the column to the upper part. This results in significant temperature increase due to the heat of wetting of the coal, which is exothermic. During this stage, one of the key off-gas parameters, Graham's Ratio – defined as the ratio of the carbon monoxide concentration to oxygen deficiency expressed as a percentage, also increases as shown in Figure 2. This is most likely a combination of surface oxidation of the coal and oxygen access to the macropore system of the coal. This effect is even more pronounced in low rank coals.

After approximately two days, the coal becomes moisture saturated and evaporation begins to dominate the temperature history, with resultant cooling of the lower half of the column. The time to moisture saturation depends on the difference between the starting moisture of the coal and the moisture holding capacity of the coal. The Graham's Ratio however, does not begin to drop in response to this cooling effect until a day later.

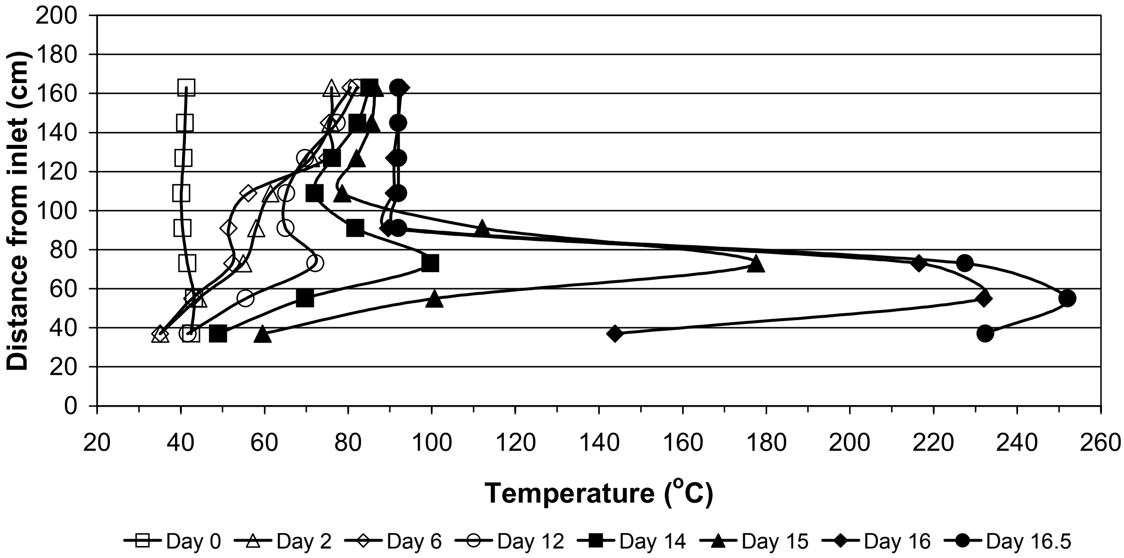

FIG. 4 - Temperature profile of a high-volatile bituminous coal self-heating in the UQ 2-metre column

Between day 4½ and 6½ a transition stage occurs, where the overall temperature and off-gas conditions remain reasonably static. This is followed by a significant increase in temperature between 37-118cm in the column due to coal oxidation, and a decrease in temperature between 118-145cm due to evaporation. During this stage the Graham's Ratio remains fairly constant with minor fluctuations in response to diurnal changes, which also affects the coal temperature. This test was conducted in the middle of winter when the diurnal flux was at its greatest.

After day 11 there is an exponential rise in the Graham's Ratio, which goes off-scale after day 14 due to limitations of the instrumentation. A gasbag analysis beyond this point indicated 4.49 and 6.62 for the Graham's Ratio at days 15 and 16 respectively, consistent with the rampant self-heating taking place in the column. The significance of this dramatic increase in oxidation rate can be attributed to the coal having reached its critical moisture content. Hamilton (2001) showed that such a value exists for different coals by doing repeated R_{70} tests at different moisture contents until thermal runaway could be achieved. For the subbituminous coals tested he found that this critical moisture value was below the air-dried moisture content of the coal and was also dependent on the mineral matter content of the coal.

By day 12 the hotspot is clearly visible at 73 cm from the air inlet (Figure 4), and by day 15 it begins to rapidly migrate towards the air inlet as the leading edge of the hotspot dries the coal and gets first access to the air.

OFF-GAS ANALYSIS OF GASBAG SAMPLES

The gas evolution associated with the column heating is shown in Figures 5 and 6. The coal has some residual methane (265ppm) and carbon dioxide (2.3%) present as seamgas, which desorbed from the coal while it equilibrated to 40°C. During the initial stage of moisture condensation there is a noticeable increase in hydrogen and carbon monoxide (Figures 5 and 6 respectively). This is followed by a steady decline in gas levels until the critical moisture content of the coal is reached at day 11 and a hotspot develops. At this point the carbon monoxide shows a 40% increase, while at the same time the hydrogen concentration increases by 60% and the carbon dioxide increases by 20%. The corresponding hotspot temperature at this stage was 70°C.

By day 13 the hotspot has reached a temperature of approximately 80°C. The hydrogen has increased by over 300%, carbon monoxide by over 400%, methane by 100% and carbon dioxide by 80%. Ethane and ethylene are absent and do not appear until much higher temperatures are reached.

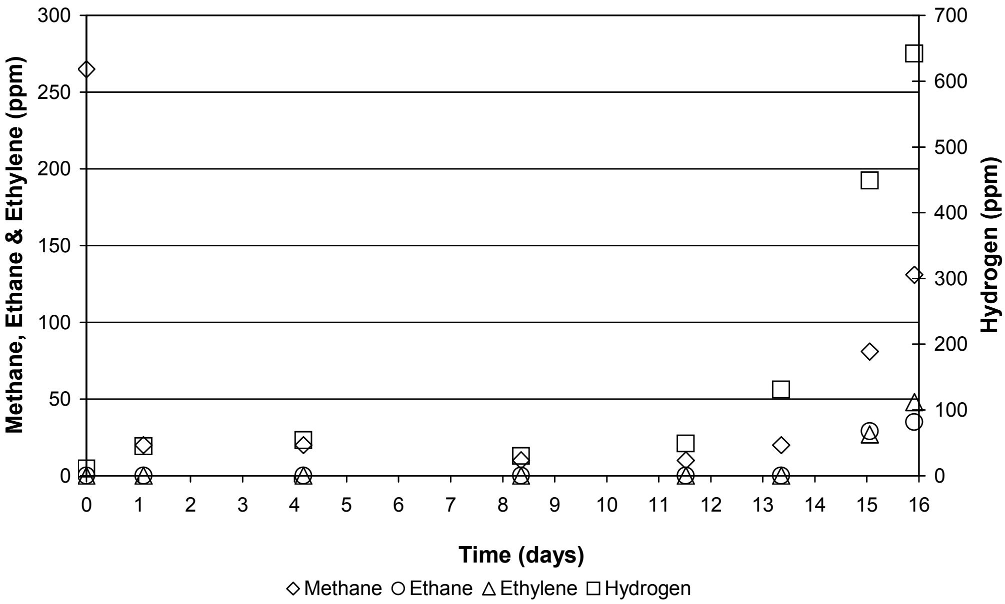

FIG. 5 - Off-gas evolution history from a high-volatile bituminous coal self-heating for methane, ethane, ethylene and hydrogen

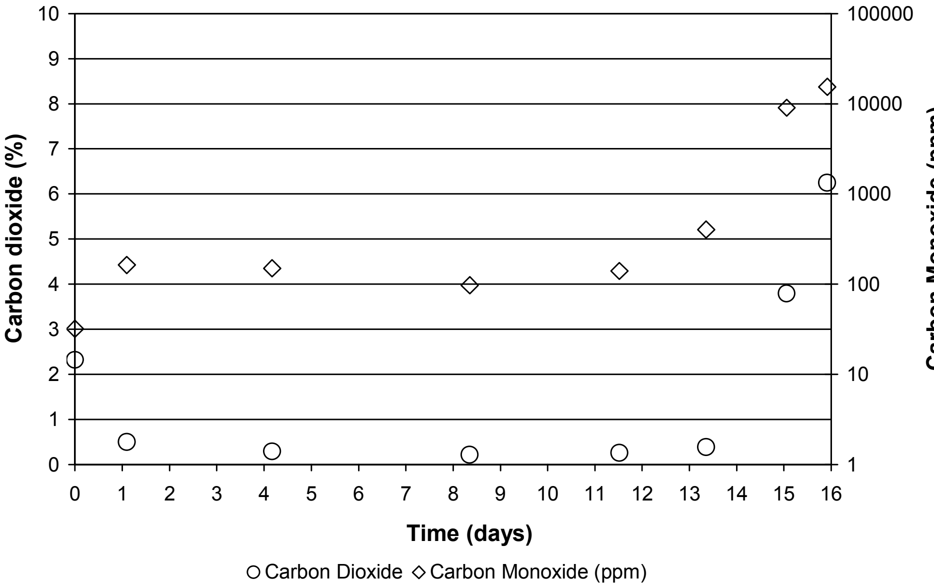

FIG. 6 - Off-gas evolution history from a high-volatile bituminous coal self-heating for carbon dioxide and carbon monoxide

IMPLICATIONS OF SELF-HEATING DEVELOPMENT FOR LONGWALL OPERATIONS

Moisture transfer is the key factor in self-heating development. If this does not take place then a heating cannot develop. Any form of air leakage path is capable of generating a heating . If it begins to dry the coal out below its critical moisture content then accelerated oxidation will take place. The stages of heating development in the column closely match reports from mines that have experienced heatings in the past. Visible signs of sweating would appear on the return side of a heating due to the moisture transfer of the airstream. The hotspot itself may be only very small and just inbye of the free surface of the air intake point, where temperature elevation of the coal would be virtually undetectable.

The accelerated heating due to "dried coal" oxidation has implications for gas drainage, where this is applied. Dry, dusty coal will grab any moisture available from the ventilation and begin to heat in response to the heat of wetting. This will in turn increase the rate of oxidation, which will in turn provide another heat source. In essence this would be double jeopardy. A situation such as this has already been simulated in the UQ 2-metre column (Phillips, 2002). Instead of a small hotspot developing the dimensions of the hotspot were grossly enlarged and the rate of self-heating was far more rapid than usual.

Interpretation of off-gas signatures requires careful monitoring and sound technical experience in understanding the stages of a heating. There are no simple rules of thumb that can be applied except that increasing gas trends warrant closer examination. With the assistance of bulk testing in the column patterns of gas evolution can be identified for individual coals that take into consideration the bulk chemistry that is taking place. This has been a major deficiency in past investigations and confusing information has been generated that may be providing a false sense of security to some mining operations.

CONCLUSIONS

As soon as coal is exposed to the air it will begin to dry. Moisture removed will be transferred further downstream by the air current and cause the coal temperature to rise due to the heat of wetting effect. Once the coal dries to a critical moisture level (below the air-dried moisture content), rapid oxidation takes place causing the coal to self-heat and generating a hotspot. This hotspot will then migrate towards the air source and if allowed to go undetected can propagate to an ignition once it daylights to a free surface.

Off-gas signatures are unique to individual coals during a heating and may vary dependent on the conditions to which the coal is subjected as well as the intrinsic properties of the coal. It is important therefore to monitor the changes occurring in gas evolution with time. Bulk coal self-heating tests provide the opportunity to recognise off-gas patterns that can assist mine operations to identify the development of an underground heating. In the example presented in this paper, the stages of heating development are reflected by the off-gas evolution. For this particular coal, hydrogen and carbon monoxide give the earliest indication of a heating. Closely monitoring the Graham's Ratio would provide a definite indication of heating development.

As more tests are completed with the UQ 2-metre column, a far better understanding of coal self-heating is being obtained. Further study is needed on the effects of physical parameters such as airflow rate, particle size and, pile porosity. These will be conducted in parallel tests using two columns.

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